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NETWORK MODEL OF FREE CONVECTION

WITHIN INTERNALLY HEATED POROUS MEDIA*#

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A hypothetical core-disruptive accident (HCDA) in a liquid metal fast breeder reactor (LMFBR) may result in the formation of an internally heated debris bed. Considerable attention has been given to postulated mechanisms by which such beds may be cooled. It is the purpose of this work to demonstrate a method for computing the heat transfer from such a bed to the overlying sodium pool due to single-phase, free convection.

Theoretical investigation in this area is rather limited, with most studies relying to some extent on experimentally determined parameters and correlations. Among the more successful are the works of Dhir and Catton[1], Hardee and Nilson[2], and Buretta[3]. In this

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effort we will model the structure of the debris bed and seek exact, steady-state, free convective solutions for the fluid mechanics and heat transfer within that model based on first principles.

The porous media is modeled as a network of interconnected tubes whose walls transfer the heat to a variable density fluid flowing within them. A similar model was used by Fatt[4] in treating forced incompressible flow in porous beds and an analogous method has been used by Otis[5] in treating pulmonary airway mechanics. In comparison with tube bundle models a network system can be adapted to any degree of anisotropy, and is far less complex than sphere pack models. Tube lengths and radii can be related to debris bed granular size, porosity, permeability, etc. For incompressible flow, Fatt found 20 x 20 networks to be sufficiently large, and that a two dimensional network is equivalent to a three dimensional case.

For our model, the following assumptions have been made:

1. Rectangular two dimensional network of cylindrical tubes.
2. Infinite radial and zero axial conductivity in the fluid and in the solid surrounding each tube.
3. Single phase fluid whose density is a linear function of temperature.

4. Complete mixing at the nodes.
5. Heating done only through tube walls and not at the nodes.

For the i^{th} tube, the nondimensional equation for the fluid mechanics is given by:

$$\Delta P_i = R_o \frac{\ell_i}{\gamma_i^4} \overset{o}{m}_i - (1+\beta_o-\beta_o\Theta_i)\ \ell_i \sin \alpha_i \tag{1}$$

where

ΔP_i = pressure difference between tube ends,
$\overset{o}{m}_i$ = mass flow rate,
Θ_i = fluid temperature midway through tube,
ℓ_i = tube length,
γ_i = tube radius,
α_i = inclination of the tube axis,
R_o = resistance factor, and
β_o = bouyancy factor.

The equation describing the heat transfer to the fluid is given by:

$$\Theta_i = \Theta_{ie} + \frac{H_i \gamma_i \ell_i}{\overset{o}{m}_i} \tag{2}$$

where

Θ_{ie} = fluid temperature at tube inlet, and

H_i = local heating rate.

With this choice of variables, the fluid mechanics yields a linear relationship between midpoint temperature and mass flow whereas the heat transfer gives a hyperbolic relation. If this were a single tube problem, a solution would be the intersection of these two curves. For the network, the solution can be envisioned as the intersection of much more complex, interdependent, multi-dimensional surfaces whose character will be similar to the simple case.
We can expect a maximum of one solution with positive temperatures. In some cases no real solutions will be found indicating that no purely convective solution exists.

For each tube there will be two equations due to the fluid mechanics and heat transfer. For each node, there will be an additional mixing equation. The total number of equations will be five times the number of nodes.

Computations have been made using relatively small rectangular networks to simulate finite sized beds with adiabatic walls and base. The bed depth is taken to be 0.05 meters, the sodium pool temperature is 673K and the tube geometries are varied to simulate a void fraction which varies from 60% at the surface to 40% at the bed base. The entire distribution of velocities and temperatures is calculated for each example with the results summarized here.

network size	2 x 3	5 x 3	5 x 9
specific power	1.5 kW/kg	1.5 kW/kg	1.5 kW/kg
bed width	0.03 m	0.01 m	0.03 m
mass exchange flux between bed and pool	0.14 kg/m^2	0.19 kg/m^2	0.12 kg/m^2
maximum bed temperature	991K	998K	968K

The preceeding cases, although limited in size and physical significance, demonstrate some of the capabilities of the technique for analysis of a rather complex phenomena. The technique depends on the basic equations being algebraic. An increased amount of physical detail can be treated provided such phenomena can be adequately described by algebraic equations. For example, two phase flow can be treated with fifth degree equations. To examine the effect of low Prandtl number, axial conductivity could be incorporated. Results thus far are for overly simplified cases, but show the tractability of a method which could be a useful tool in the phenomenological study of heat transfer within porous media.

References

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